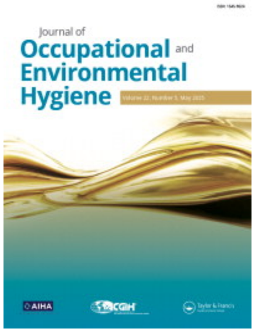

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REPORT

Airborne lead exposures during artisanal lead mining and gold ore processing in Zamfara, Nigeria

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ABSTRACT

Artisanal mining in Nigeria is growing along with the increase in the price of metals. However, self-employed miners, particularly in the northwest of the country, have brought extensive environmental contamination and severe lead poisoning from the lead content in the ore. This study assessed airborne lead exposures to miners during lead mining and gold ore processing in three villages in Zamfara State, Nigeria. Personal air samples were collected and analyzed for lead content. Gold processing operations were classified by task, including: manual mortar and pestle grinding, hammer crushing, and mechanical stone crushing and grinding operations with diesel-powered equipment. Separately, exposures were evaluated among underground lead miners. This study collected a total of 47 air samples, including 32 from gold ore processing sites and 15 from lead mining sites. The results indicated that underground miners were exposed to airborne lead at a mean concentration of 0.48 mg/m^3, or approximately 10-fold the United States Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL). Furthermore, miners at gold processing sites were exposed to airborne lead at a mean concentration of 1.59 mg/m^3 for both mechanical and manual tasks, which is approximately 32-fold the PEL. Manual gold ore processing resulted in mean airborne lead exposures of 1.74 mg/m^3, and those using mechanical methods had a mean concentration of 1.52 mg/m^3. The results also indicated that the order of airborne lead level exposure was as follows: mortar and pestle operators > crusher operators > hammer operators > grinder operators > underground lead miners. Lead mining operations and gold ore processing consistently had elevated airborne lead at levels, posing risks of acute lead poisoning, and are likely contributing to take-home lead exposures observed in these communities. These results are consistent with the lead contamination of soil observed in housing compounds and at processing sites in this region. To address these risk factors, safer mine training and the adoption of wet methods were encouraged along with changes to personal hygiene practices and other measures to mitigate exposure and to protect miners and their communities.

KEYWORDS
Airborne lead exposures; artisanal mining; gold ore processing miners

Introduction

Artisanal mining has experienced significant growth, yet it is often linked with crude practices posing threats to health and resulting in environmental contamination (IISD 2017). In 2017, around 40.5 million individuals were directly involved in Artisanal and Small-scale Mining (ASM) globally – a large increase from 13 million in 1999. This contrasts with the mere 7 million people employed in industrial mining in 2013 (IISD 2017). More recently, there has been growing evidence that self-employed (informal) miners have expanded into mining cobalt, lithium, coltan (tantalum), tin, lead, and other metals.

Mining is an important source of income in many African countries, and most countries in the region report that the sector is the largest exporter (Sinkala 2009). As employment in industrial mining is shrinking due to improved mechanization and mine closures, the number of informal miners continues to increase. The mining sector in Nigeria is primarily composed of an estimated 500,000 artisanal and small-scale informal miners in operation, and over 90% of solid mineral production is done by these

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miners (Idowu et al. 2013; Nnaji and Omotugba 2016).

In Northern Nigeria, artisanal gold mining and ore processing have been associated with extensive environmental contamination and acute lead poisoning. More recently, lead mining has started in Zamfara State, although artisanal lead mining in other regions of Nigeria has been ongoing for at least 40 years (Ozobialu et al. 2023). Nigeria exported 50,000 tons of lead between 2013 and 2017, but exports have grown to almost 54,000 tons in 2020 (NEITI 2020; Sumaina 2018). Nigeria has no domestic smelter operations, and all lead ore sourced from informal miners must be exported for processing.

Although gold ore is extensively processed to extract the gold, lead ore is generally sold unprocessed and in bulk. The gold ore found in the Zamfara State has a lead content of about 8.5% (89,500 ppm) alongside notable concentrations of various other heavy metals (Bartrem et al. 2014). Other studies revealed that ore processing caused extreme contamination in villages throughout Zamfara State, with up to 18.5% (185,000 ppm) lead in soil samples (Plumlee et al. 2013).

In Zamfara State, lead and gold are mined in underground pits up to a depth of 30 m with simple mining tools including shovels, pickaxes, hammers, and chisels. The mined lead ore is stored at the mine site or taken home before being sold for export. In March 2010, Doctors Without Borders/Medecins Sans Frontieres (MSF) identified extensive acute lead poisoning in communities in Zamfara State in northwestern Nigeria, which resulted in the death of hundreds of children (Lo et al. 2012). Although subsequently, there has been well-documented evidence of lead exposures from mining and processing the local gold ore in this region, no studies have reported on airborne lead exposures from manual processing tasks. There is also a lack of exposure data from artisanal lead mining.

In 2017, concerns were raised as some of the gold miners in the impacted villages had shifted to underground lead mining to supplement their income. At the same time, MSF noted that childhood lead poisoning persisted in their home communities. Exposures associated with this activity were not previously known, and it was unclear what role that lead mining played in the ongoing community exposure and contamination of homes. As recontamination of some home compounds was observed in the years after extensive soil remediation was conducted, it was suspected that informal lead miners were taking home lead ore and/or lead dust, which was contributing to ongoing lead poisoning in these villages.

In 2018, the current study was initiated to measure airborne lead during gold ore processing operations and lead mining occurring near three villages. The purpose was to use exposure information gained to better advise miners to adopt control measures to reduce the risk of lead poisoning and contamination of these communities.

Methods

Personal airborne lead air samples were collected during work activities in gold ore processing and at lead mining sites. These work areas were located in areas outside of Abare, Dareta, and Bagega villages in the Anka local government authority (LGA), Zamfara State. The villages were selected for the study as they were part of the cohort that had a large number of children in the lead poisoning treatment program run by MSF.

Before commencing this exposure assessment, community and mining leaders were involved in the general planning and attended lead hazard awareness training sessions. Training was provided to miners and ore processors in small groups, covering the hazards of lead, mercury, and silica dust and improved work practices to reduce exposures during processing and mining. The training, which took place both in classrooms and on-site, was offered in the local language, lasted three hours per session, and included discussions.

Gold ore processing was done by men, women, and teenagers using manual and mechanical processes, which varied by location. Processing operations were classified into task groups based on the authors' observations as follows: mortar and pestle use, hammer operations, and mechanical crushing and grinding. At the larger gold ore processing areas outside Abare and Bagega villages, there were hundreds of miners in diverse roles involved in processing and transporting ore. Younger people generally perform manual tasks, including hammering rock, using the mortar and pestle, feeding mechanical crushers and grinders, packing crushed or ground ore, sluicing, and combining mercury with concentrated ore to form an alloy (amalgamation). Adults were mostly mining ore, running mechanical crushing and grinding equipment, transporting bags of ore from mining sites to processing areas, and from processing sites to sluicing areas.

Separately, the exposures were evaluated among underground lead miners using manual tools to remove ore outside of Dareta. Lead mining operations were conducted primarily by men. In this mining

Table 1. Personal airborne lead exposures at gold ore processing and during underground lead mining.

Job type/Work activity	Number of samples	Mean lead (mg/m^3)	Geometric mean lead (mg/m^3)	Standard deviation	Range (mg/m^3)	Range of sampling durations (Min)	Ratio lead/PEL
Manual – Mortar and pestle	4	3.08	2.30	2.47	0.83–6.2	336–431	61.6
Manual – Hammering	5	0.67	0.44	0.76	0.19–0.57	172–287	13.3
Mechanical – Crushing	11	2.61	0.64	4.78	0.08–16	217–294	52.2
Mechanical – Grinding	12	0.53	0.27	0.67	0.05–1.7	217–321	10.5
Underground lead mining	15	0.48	0.35	0.33	0.02–1.1	224–314	9.6

operation, it was noted that approximately 50 people worked intermittently at the site in various roles.

At both the lead mining and gold ore processing centers, miners organized themselves into specific tasks as indicated by work leaders. Work hours were highly variable, and miners and processors were selected to participate from those actively working and expected to stay for a full shift. Each sample represented a different miner, and no miner or processor was sampled more than once.

Air sampling was conducted during the dry season. This timing was important to capture worst-case conditions, as the processing was typically done with dry ore without any exposure prevention precautions.

A total of 47 personal airborne lead samples were collected, including 32 at gold ore processing sites and 15 at lead mining sites. Battery-operated air sampling pumps (SKC Aircheck sampler Model 224-PCXR4) were calibrated and set at the flow rate of 2.0 L/min before sampling using Mesa Labs Bios DryCal Defender 510 (primary standard flow meter), and post-calibration was done after sampling. There were no deviations of more than ±5%. Sampling equipment was placed on employees for a full workday of variable length. In the lead mining area, pumps were attached to workers before they went underground and were returned at the end of their shift.

Air samples were collected with 37 mm MCE filter cassettes placed in the breathing zone in a downward position. Sampling times ranged from 172 to 431 min for gold ore processing and 224 to 314 min for underground lead mining. All air samples represent full shift exposures equivalent to a time-weighted average (TWA) as they were monitored from the start to the end of each individual's workday. Working hours at these sites were inconsistent, but the duration of work was generally 4–8 hr total per day. Samples were sent to Bureau Veritas (Novi, Michigan), an American Industrial Hygiene Association accredited laboratory for lead analysis with the National Institute for Occupational Safety and Health 7303 Elements by ICP method, and the limit of detection (LOD) was 0.001 mg/filter. Results were reported in mg/m^3. IHSTAT software was used for the statistical assessment. For this study, the OSHA Permissible Exposure Limit (PEL) for lead (0.05 mg/m^3) was utilized as a benchmark for evaluating exposures among miners and processors.

Results

Table 1 summarizes the results for airborne lead exposures for task-specific ore processing and underground lead mining activities, which present the mean, geometric mean, standard deviation, range, and the ratio of the mean airborne lead exposure to the PEL for each task.

The overall mean and median for all mechanical gold ore processors monitored were 1.52 mg/m^3 and 0.26 mg/m^3, respectively. All lead exposures for mechanical crushing operators exceeded the PEL, with a mean of 2.64 mg/m^3, and the crusher operators' exposure levels ranged from 0.07 mg/m^3 to 16.0 mg/m^3.

Airborne lead exposure samples during mechanical grinding operations had a mean of 0.53 mg/m^3 (range 0.05 to 1.7 mg/m^3), which is almost 11-fold higher than the PEL. The mean and median for all manual gold ore processing were 1.74 mg/m^3 and 0.83 mg/m^3, respectively. All lead exposure from manual hammering had a mean of 0.668 mg/m^3 (range 0.19 to 0.57 mg/m^3). Mean lead exposures during mortar and pestle operations were 3.08 mg/m^3.

As shown in Table 1, 14 (93%) of the 15 samples from underground lead mining exceeded the PEL and with a mean of 0.48 mg/m^3 (range 0.02 to 1.1 mg/m^3). Table 2 provides individual airborne lead exposure during gold ore processing and Table 3 lists results for underground lead mining.

Discussion

Gold ore processing

This study demonstrated that both mechanical and manual gold ore processing resulted in mean airborne lead levels exceeding the PEL. Miners were exposed to surprisingly high levels of airborne lead from manual processing with mortar and pestle and hammering. The highest exposures observed were among those using a mortar and pestle to grind ore. The order of airborne lead level exposures by task, as shown in Table 1, is as follows: mortar and pestle operators

Table 2. Airborne lead exposures in gold ore processing.

Sample ID	Work activity	Sampling Time (min)	Lead (mg/m^3)	Lead (mg/m^3)/PEL
Lo1/06/10	Mortar and pestle operator	431	0.83	16.6
Lo2/06/10	Mortar and pestle operator	336	3.9	78
Lo3/06/10	Mortar and pestle operator	373	1.4	28
Lo4/06/10	Mortar and pestle operator	419	6.2	124
L02/15/03	Crusher operator	291	5.8	116
L01/08/02	Crusher operator	278	0.26	5.2
L02/15/02	Crusher operator	275	16	320
L03/15/02	Crusher operator	266	0.07	1.34
L03/08/02	Crusher operator	271	0.59	11.8
L02/26/04	Crusher operator	256	0.22	4.4
L03/26/04	Crusher operator	240	2.3	46
L02/10/05	Crusher operator	217	0.33	6.6
L03/03/05	Crusher operator	276	2.9	58
L04/03/05	Crusher operator	263	0.08	1.62
L02/09/05	Crusher operator	294	0.2	4
L02/08/02	Grinder operator	273	1.7	34
L04/08/02	Grinder operator	260	0.2	4
L01/15/02	Grinder operator	276	0.17	3.4
L04/15/02	Grinder operator	264	0.16	3.2
L01/15/03	Grinder operator	287	0.6	12
L01/26/04	Grinder operator	252	0.10	1.98
L04/26/04	Grinder operator	236	0.34	6.8
L03/10/05	Grinder operator	275	0.62	12.4
L04/10/05	Grinder operator	268	2.1	42
L01/10/05	Grinder operator	217	0.2	4
L01/03/05	Grinder operator	321	0.08	1.54
L02/03/05	Grinder operator	278	0.05	0.92
L03/15/03	Hammer operator	275	0.19	3.8
L04/15/03	Hammer operator	269	0.57	11.4
L03/09/05	Hammer operator	287	0.38	7.6
L04/09/05	Hammer operator	282	2	40
L01/09/05	Hammer operator	172	0.2	4
		Mean:	1.59	31.71
		Standard deviation	3.07	

Table 3. Airborne lead exposures during underground lead mining.

Sample ID	Sampling time (min)	Lead (mg/m^3)	Lead (mg/m^3)/PEL
L01/20/03	267	0.31	6.2
L02/20/03	264	0.02	0.3
L03/20/03	224	0.37	7.4
L04/20/03	258	0.45	9
L01/13/03	314	1.1	22
L02/13/03	313	0.49	9.8
L03/13/03	305	0.16	3.2
L01/24/04	313	0.46	9.2
L02/24/04	313	0.18	3.6
L03/24/04	313	1.1	22
L04/24/04	313	0.36	7.2
L01/02/05	245	0.39	7.8
L02/02/05	233	0.33	6.6
L03/02/05	247	1.0	20
L04/02/05	224	0.42	8.4
	Mean:	0.48	9.5
	Standard deviation	0.33	

> crusher operators > hammer operators > grinder operators. There was considerable variability within the mechanical tasks monitored for gold processing, with 34- to 200-fold differences observed in lead exposures. The observed variability in exposure concentrations within tasks may be partially attributed to differences in the concentration of ore from various mine sites.

The observed lead exposures among gold ore processors in this study were higher than those reported in neighboring country of Niger. The pre-intervention mean exposure from ore processing in Niger State was 0.96 mg/m^3 compared to 1.59 mg/m^3 for a similar mixture of mechanical and manual operations reported in this study (Gottesfeld, Tirima, et al. 2019). These differences may be due to higher concentrations of lead in the ore than in Niger State and variable conditions from monitoring during wet and dry seasons. In Niger State, there were fewer processing machines, which were generally operating for shorter periods compared with the processing areas covered in this study. Furthermore, the same study demonstrated that low-cost interventions to convert dry ore processing to wet methods with spray misting can effectively reduce airborne lead levels by 95% (Gottesfeld, Tirima, et al. 2019). They also documented that the combination of improved work practices and personal hygiene measures contributed to a 32% reduction in geometric mean blood lead levels over 19 months among miners and processors (Gottesfeld, Meltzer, et al. 2019).

Lead mining

According to the Nigerian Customs Service, lead is mostly exported in raw form, which typically contains

5% lead (Sumaina 2018). In Nigeria, lead ore exports grew by more than 360% between 2013 and 2022 (UN Comtrade Database 2023). In 2022, 99% of exports were destined for China (UN Comtrade Database 2023). Artisanal lead mining will likely continue to expand in Nigeria due to its profitability, the demand for raw lead ore exports, and the geographical spread of artisanal mining to additional regions despite environmental and health concerns.

Artisanal underground lead mining in Zamfara resulted in mean airborne lead levels that exceeded the PEL by 10-fold. Due to the lack of airborne exposure data from lead mining, the results were compared with published lead exposure data from industrial activities. The review study conducted by Gottesfeld and Pokhrel (2011) on exposures from lead-acid battery manufacturing and recycling plants across 37 developing countries revealed that airborne lead concentrations averaged 0.367 mg/m^3. A similar mean lead exposure of 0.48 mg/m^3 among underground lead miners was observed. A study assessing lead exposures among workers in a lead battery recycling plant and manufacturing plant in Kenya also reported similar mean personal exposures of 0.427 mg/m^3 and 0.349 mg/m^3, respectively (Were et al. 2012).

This study represents the inaugural attempt to assess airborne exposures during artisanal lead mining. The growing presence of self-employed lead mining operations has been reported in Nigeria and globally (Lu and Lora-Wainwright 2014; Nakata et al. 2022; Ozobialu et al. 2023). In some cases, artisanal lead mining was taken up after large-scale mines were closed, as reported in western Hunan province in China and Zambia (Lu and Lora-Wainwright 2014; Nakata et al. 2022).

Extensive environmental contamination has been documented in China from the proliferation of self-employed lead mining, and blood lead levels of local residents were reportedly ranged up as 60 µg/dl (Lu and Lora-Wainwright 2014). A study examining environmental lead contamination from another lead-zinc mining site in Nigeria suggested that these exposures contributed to higher blood lead levels among residents (Bello et al. 2016). The study documented lead-contaminated soil, household floor dust, water, and crops in the community, potentially related to lead mining activity. Another study tested agricultural soils in an area with lead-zinc mining in southeastern Nigeria and reported that 87% of soil samples analyzed were greater than the Canadian Environmental Quality Guideline (CCME) soil lead level of 200 mg/kg (Obiora et al. 2016).

Community exposures

This study was undertaken in part to better assess sources of community lead exposure, as it has been well understood that gold ore processing was a key risk factor in elevated blood lead levels among children in these villages (Kaufman et al. 2016). As gold ore processing was moved to locations outside of residential areas in these communities, blood lead level monitoring of children continued to identify children with elevated exposures. The emergence of lead mining was cited as another possible source of take-home exposure that may be contributing to these observations. The results from personal air sampling suggest that lead miners and ore processors may be contributing to community exposures.

Lead contamination can be transmitted from miners and ore processors through the dust on clothing, shoes, hair, and skin, and deposited in their homes. These types of take-home exposures are well-documented sources of childhood lead poisoning, especially where sufficient personal hygiene measures are not in place (Lo et al. 2012).

A study conducted in Australia among formal sector lead-zinc-copper mine workers traced the sources of community exposure with isotopic analysis (Chiaradia et al. 1997). Dust shaken from the clothes of my employees contained a significant amount of lead up to 3,000 ppm (Chiaradia et al. 1997). Vacuum cleaner dust in the houses of these miners had a median lead concentration of 470 ppm, with isotopic analysis showing that between 40 and 100% of the lead came from mining sources (Chiaradia et al. 1997).

The evidence of environmental lead contamination from these studies, along with the soil lead levels observed in the subject villages, suggests that occupational take-home exposures are likely a significant contributor to childhood lead poisoning in Zamfara. Efforts to reduce this exposure source have focused on improving personal hygiene practices with training programs and the introduction of handwashing stations, shower facilities, and changing areas at lead mining and gold ore processing sites. Over time, miners adopted these practices, and in these communities, childhood blood lead levels were gradually reduced (Thurtle et al. 2023).

This study's findings emphasize the significance of uncontrolled lead exposures in artisanal mining as a pressing public health concern in mining communities. Efforts to control these exposures and reduce take-home contamination will improve health outcomes in impacted communities over time.

The air monitoring results reported here suggest that occupational exposures to lead in Nigeria may be linked to acute health outcomes among adults. However, previous efforts to quantify exposures have mostly focused on health assessments of children living in these communities. Artisanal lead and gold mining in low-income countries warrants further investigation to better understand the health risks to both miners and local communities.

Limitations

This study presents data on personal airborne lead monitoring; however, several limitations must be acknowledged. The sample size was small, especially for gold ore operations, which limits the generalizability of the findings to other mining populations. Moreover, the variability in lead content within gold ore increases variability in air sample results, potentially influencing the repeatability of exposure assessments during ore processing. Another limitation is that the study did not assess blood lead levels (BLLs) of miners and processors, which is a critical measure of lead exposure. Therefore, the direct impact of airborne lead exposures on BLLs and health outcomes was not explored in this study. Additionally, while the results suggest that airborne lead exposures may contribute to take-home exposures, conclusive evidence would require further studies incorporating environmental sampling and BLL assessments of miners and their families. Future research efforts should consider addressing these limitations to provide a comprehensive understanding of lead exposure risks in artisanal mining and processing environments.

Conclusion

High levels of airborne lead exposure were observed among all mining and ore processing tasks. The average airborne lead exposure across all lead mining and gold ore processing operations exceeded the PEL at concentrations suggesting a potential risk of acute lead poisoning to miners and their communities. Additionally, these consistently elevated airborne exposures suggest a high likelihood of environmental lead contamination in areas with ongoing mining and processing.

To effectively reduce exposures to airborne lead and enhance occupational health and safety for miners and communities, the implementation of a combination of work practices and personal hygiene measures is required. In response to these findings, a mine program focused on safety and health was introduced that included the adoption of wet practices in both processing and underground lead mining areas and the promotion of personal hygiene practices, including hand washing, showers, and changing facilities. Comprehensive training programs were introduced for both miners and community leaders, along with the promotion of personal hygiene practices at both lead mining and processing sites. Knapsack-mounted sprayers were also introduced for manual processing and underground lead mining to effectively reduce dust exposures. A health and safety committee was established in each village to ensure the continuity of the safety and health-focused mining program.

Expanding these efforts in Zamfara State and throughout Nigeria to protect public health should be a priority for federal and state governments. Immediate action is needed to introduce occupational health and safety measures, including the use of wet methods for both mechanical and manual ore processing as well as underground lead mining. The Federal Government of Nigeria must invest in occupational health and safety-focused mining programs and adopt comprehensive regulations to reduce lead exposures among miners and protect public health in these communities. Although the adoption of occupational lead regulations will not solve these problems, it would be a first step in increasing awareness and providing guidance to miners.

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Data availability statement

The complete data presented in this paper are provided as a supplemental document.

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